A Comprehensive Review of BeagleBone Technology: Smart Board Powered by ARM

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Abstract

In the last few years, there have been a rapid increase towards single-board microcontrollers. These days, trend has shifted towards development of full-fledged credit-card sized computer's like Arduino Mega2560, Raspberry Pi, Orange Pi, Chip and even Beaglebone. These boards are low cost, low power, easy deployable and has user-friendly configurable options. Beaglebone technology is speeding up and growing like anything as millions of pieces are sold worldwide till date. Beaglebone boards are showing tremendous increase in adaptability and implementation in diverse areas like Robotics, Drones, Smart Homes, IoT devices, Linux and Cloud Computing Servers and even more. The aim and objective of this research paper is to provide a comprehensive review of Beaglebone Technology, various Beaglebone boards available till date with their technical specifications along with various research areas which can enable researchers and industry professionals to take up Beaglebone Technology and develop wide range of ready to use efficient and low cost products.

Keywords: Beaglebone, ARM, Beagle, Beaglebone Black, Linux, IoT, Drones, Sensors, Android

1. Introduction

During the last couple of years, various development platforms have come under the light of sun and it has led to the development of various boards cum Credit Card Sizes low-cost handheld computers like Arduino Zero, Arduino 101, Intel Galileo, Raspberry Pi B, B+ Model, Orange Pi, Panda Board, ORDIOD Board *etc*. These boards support installations and deployments of various popular Operating Systems like Ubuntu, Raspbian, Windows 10 IoT and even various versions of Android.

As, these development boards have System-On-Chip (SoC) and are powered by ARM Technology in their heart core which makes these boards power efficient, low-cost and provide widened platform for researchers and hobbyists for various project developments on different areas of computing. These boards facilitates the following characteristics [1]:

- Plethora set of Ports options available for users like: GPIO, SPI, UART, PWM, I2C *etc*.
- Various communication interfaces in terms of TCP/IP, UDP and Field-Bus based protocols.
- Multi-Platform Operating System support like Android, Linux, Windows 10 providing various functionalities in terms of multi-tasking, multi-user and real-time applications.
- Proper documentation support (via Reference Manuals) in terms of Hardware, Software by core manufacturer and third party companies.

- Rapid and Continuous Enhancement and Improvement in ARM Technology (ARM Processors Generations)leads to enriched features and provides modularity and flexibility to various Development boards.
- Long term availability and full technical support via Manufacturers, Development Forums and Open Research Groups.
- Low Cost in terms of development and maintenance.
- Enhanced features in terms of Remote Administration/Control via various tools like Putty, VNC Server *etc*.
- High-performance cum broadened scope for various out-of-the-box computing projects like Robotics, Automation, Drones, Object Recognition *etc*. to name a few.
- Hardware Virtualization Support.

1.1. Overview of ARM Technology [2]

ARM (originally 'Acron RISC Machine' now known as 'Advanced RISC Machine') basically belongs to family of RISC instruction set architecture for processors in computers. ARM was basically designed for developing low-cost, power-efficient and performance processors. ARM supports both 32-Bit and 64-Bit architectures supporting clock frequency upto 1GHz. ARM integrates SoC (System-on-chips) technology which facilitates integration of memory, ports and other interfaces. Because of its unique features and interfacing's, ARM technology is currently used in almost every development board. Till 2014, 50 Billion ARM processors have been produced powering almost every mobile device, development boards, handheld gadgets and even drones.
Because of its plethora of advantages, ARM is powering Beaglebone and its various Boards.

1.2. Basic Overview of "Beagle" Platform [1, 3]

The term "Beagle" was coined by Digi-key [4] and the first fully functional low-power single board open source computer was designed by Texas Instruments [5] along with Network Element 14 [6] and was launched on July 28, 2008. Since its launch, "Beagle Project" got a terrific response from large community of open source developers and forums to take up this board and utilizing it towards open source project developments. Till date, various flavours of boards are launched like BeagleBoard-X15, Beaglebone Black, Beaglebone, Beaglebone-xM, BeagleBoard and more than 30 Million Boards are sold world-wide till 2015.

1.3. Organization of Paper

Section II will give details of BeagleBoard Technology- Overview, Technical Specifications, Features, Why Beaglebone? and Beaglebone Board Components. Section III will provide comprehensive review of various Beaglebone boards available till date, Section IV will provide details to researchers and hobbyists regarding various projects that can be undertaken for development by using Beaglebone Open Source Smart Hardware Development technology and Section V will include conclusion and future scope.

2. Overview of Beagleboard Technology

This section of Research Paper will give overview of BeagleBoard technology by comprehensive definition, Why to choose Beaglebone platform for project development and detailed light towards Beagleboard Components.

2.1. Beagleboard- Overview [3, 7-9]

Beagleboard was originally developed and introduced by Texas instruments in year 2008 by using OMAP3530 System-on-a-chip technology with basic objective done by a small team of engineers to come out with some sort of educational board that can provide good platform to various colleges, educational and research centres/institutions across the world to teach/research/develop open source hardware based projects. Beaglebone is regarded as Giant step from Microcontrollers such as AVR, PIC, ARM Cortex M3, 8051*etc*. to full-fledged microcomputer. Beaglebone is regarded as fully functional computer like desktop or laptop.

OMAP3530 is integrated with ARM Cortex-A8 CPU, a TMS320C64x+ DSP for video acceleration and encoding and decoding audio and also supporting 2D and 3D rendering using OpenGL ES 2.0.

Figure 1. Beagleboard

2.2. Technical Specifications & Features of Beaglebone

The following are the Technical Specifications of Beaglebone:

- Processor- OMAP3530 SoC- 720 MHz ARM Cortex-A8 core
- TMS320C64+- 520 MHz HD Capable Processor supporting Video Playback of 720p@30fps
- 256 MB LPDDR RAM
- 256 MB NAND Flash Memory
- Slots- 1 USB Port, 1 USB OTG, SD/MMC Port, 3.5mm Jack, JTAG Connector, Power Socket 5V, S-Video, DVI-D, RS-232, Ethernet Interface.
- Operating Systems Supported- Android, Linux (Fedora, Angstrom, Ubuntu, Gentoo, Arch, Maemo), VxWorks, FreeBSD, Windows CE, Symbian QNX & RISC OS 5.

The following are the Features of Beaglebone:

- Low-Power Credit Card Small Size compact ergonomics.
- Large number of GPIO I/O Pins.

- High Performance Computing experience.
- Supports deterministic execution hardware via dedicated processing unit.
- Robust and Wide options for connectivity.
- Open Source Hardware technology- Giving Options to manufactures to integrate ARM Technology for developing cloned Beaglebone development boards.
- Open Source Software Technology- Giving Options to install wide range of Android and Linux flavoured operating systems.
- Support via large and continuous expanding community of developers, users and researchers.
- Supports interfacing with wide range of Analog cum Digital Sensors in turn opening doors for various IoT and Cloud based projects.

2.3. Why Beaglebone?

Beaglebone, a powerful ARM Technology based development board is widely adopted by researchers and embedded systems enthusiasts all over the world because of the following reasons [8]:

- Networking Capabilities: Beaglebone has on-board 10/100 Ethernet port. Apart from peer to peer network connectivity, it is capable for providing all sorts of networking services like FTP, TELNET, SSH and even has capability to act as web server to publish website using lighttpd web server package.
- Remote Control: As, Beaglebone has efficient networking capabilities, it also facilitates Remote Control access. In some situations, it is necessary to control Beaglebone remotely. With use of VNC/MobaXterm based software, entire graphical desktop can be viewed and edited remotely without any hiccup.
- Filesystem: As compared to Windows, Embedded Linux file systems have much enhanced security, organization and retrieval capabilities. Linux file system is known on ext3/ext4 which is pure file based system providing much better capabilities towards managing and organizing system functions/system calls as compared to FAT32/NTFS file systems.
- Time Management: Beaglebone board is equipped with NTP (Network Time Protocol) which enables accurate time synchronization via Internet time servers.
- Wide range of Programming Languages: Beaglebone has capability to support various compilers, tools and editors to facilitate users to write programming code of various programming languages like C, C++, Java, Python, Perl, Ruby, Shell Scripting, Ruby on Rails and even latest programming languages like R, Hack from Facebook is also supported.
- Supports Multitasking: As Beaglebone runs Linux operating system which has capability to run multiple-processes in terms of programs and tasks at single point of time. Beaglebone provides users with Multi-tasking capability in terms of multi-processes without hindering its performance.
- Growing Support Worldwide: As now Beaglebone has plenty of users, research groups cum institutions and Hobbyists working on several multi-platform projects, any person using Beaglebone can take help from online forums, developer communities and even manufactures are providing customer support 24x7 which in-turns makes it widely adoptable platform across other development platforms.
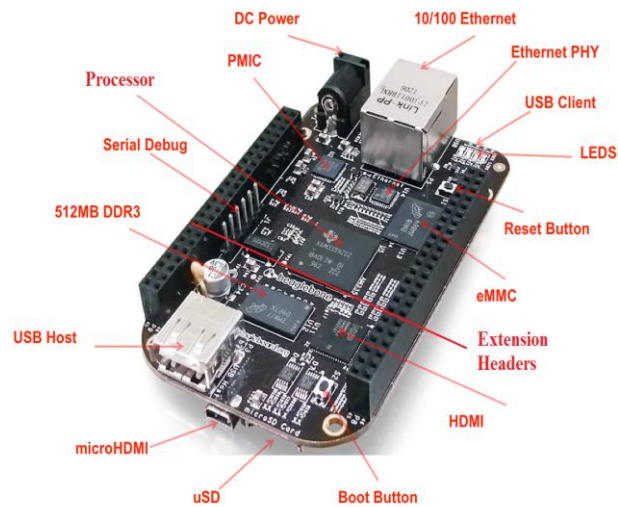
2.4. Beaglebone Board-Components [7, 8, 10]

Figure 2. Beaglebone Board-Components [Img Src: www.beagleboard.org]

The following are the components of Beaglebone Board:

1. Processor: Processor being the heart of Beaglebone board manages all sorts of controls and operations. Beaglebone processor is based on ARM Cortex A8/A15 Processor technology running at various clock speeds like 720 MHz, 1GHz, and 1.5GHz.

2. RAM: Depending on various generation models, Beaglebone boards are equipped with 128/256/512/2048 MB RAM.

3. DC Power Jack: Beaglebone requires 5V and 500 mA of DC power to operate. Along with DC power jack, 2.1 mm barrel jack connector will be required to power the board. Beaglebone facilitates over voltage protection chip upto 12V.

4. Ethernet Port: Beaglebone has on-board 10/100 standard RJ45 Ethernet Port supporting all sorts of networking protocols along with Wi-Fi connection sharing.

5. Reset Button: Reset Button reboots the board. It provides logic 1 or 0 to trigger the processor. Functioning similarly like Reset Button on computer/smartphones, it reboots the entire operating system and also provides backup from failure if lock up situation occurs.

6. USB Host: USB Host provides same features like USB port on normal computers/laptops. Beaglebone USB host ports enables users to connect various 3rd party peripherals like Keyboard, Mouse, Web Camera, Wi-Fi adopters and external storage devices like pen drives, USB card readers and hard disk drives.

7. LEDs: Beaglebone board has LED located aside power connector to indicate power ON signal when power applied to board. Most of the boards are equipped with 4 LED's with following functionalities: LED0 will be ON when Board is up and running. LED 1 will indicates microSD card operations. LED 2 indicates Active CPU active situation. LED 3 indicates flash memory access.

8. Extension Headers: Beaglebone has 2 extension headers on left and right side which facilitates integration of various electronic components like LED's, Switch's, Sensors, and Modules *etc.* for developing various projects.

9. USB Client: USB Client port is basically used for connecting Beaglebone to computer and power would be provided via USB. When connected to computer, it appears like storage device.

10. MicroSD Card Slot/uSD: MicroSD card slot facilitates integration of microSD cards to store operating systems, applications and data. Taking Beaglebone black into consideration, where operating system is stored on onboard flash memory by

default, any updates can be done via sd card slot only. Operating systems can be downloaded on Beaglebone website which can be written on SD card via Win32Disk Imager software.

11. microHDMI: microHDMI port does the work of connecting Beaglebone board to HDMI enabled Monitor/TV. It supports maximum resolution of 1280x1024 pixels.

12. Serial Debug: Serial Debug is used for serial communications to connect an FTDI TTL-232 cable or breakout board and enable text based terminal via USB.

13. eMMC/Onboard Flash Memory: Beaglebone (Black version) has operating system stored on eMMC/onboard flash memory to boot up the board without any SD card requirement.

14. Boot Button: Available only in Beaglebone black. Continuous hold of Boot Button instructs Beaglebone to boot from SD card attached on SD card slot rather than onboard flash memory.

15. PMIC (Power Management Integrated Circuit): PMIC module provides power backup solution to Beaglebone via connecting li-po batteries. These batteries will act as UPS for Beaglebone for providing backup to users over electricity failure to shut down the board or do necessary important work till batteries last long.

3. Beagle Bone Boards

In this section, a comprehensive review of various Beaglebone Boards available till date would be covered. Till 2015, 6 Beaglebone board's are available in the market. In this part of research paper, every Beaglebone board would be defined along with their respective technical specifications in addition to various areas where researchers, hobbyists and embedded systems professionals can use these boards for projects and research and development purpose's.

Beaglebone Board's are as follows:

1. BeagleBoard [11]: Beagleboard was the first board in series of Beaglebone technology and was launched on July 28, 2008. This Beagleboard comprises of OMAP3530 720MHz ARM Cortex-A8 processor and uses NEON and VFP for acceleration. Graphics of this board is powered by POWERVR and can be used as fully functional device for streaming and playing FULL-HD quality videos.
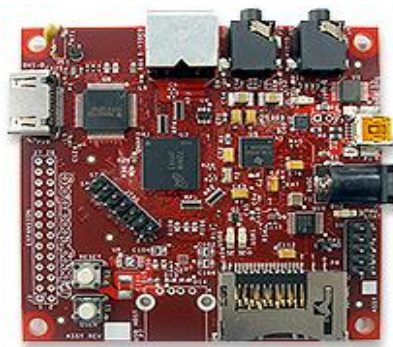

Figure 3. Beagleboard

Table 1. Technical Specification of BeagleBoard

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
OMAP3 530	ARM-Cortex A8	Power VR SGX 530	TMS 320C 64x+	128 MB	USB (OTG), DVI-D,	MMC/S D/SDIO. Ethernet -N/A	McBSP, DSS,I^2C, UART, McSPI, PWN, JTAG	Debian/ Gentoo/ Ubuntu/ Angstrom	$125

Applications: Linux based Projects, IoT Applications, Drones, Robotics

2. Beaglebone xM [12]: Beagleboard-xM was launched on September 14, 2010. Beagleboard-xM is powered by AM37x 1GHz ARM Processor. This board provides faster development environment to students, researchers and professionals and shortens project life-cycle time span. This board was a remarkable upgrade to Beagleboard by providing more processing speed, better RAM, network connectivity via Ethernet port and wide USB connectivity options. In addition to above high specifications, the board lacks onboard NAND storage because of which operating system can only be installed on microSD card.

Figure 4. Beagleboard xM

Table 2. Technical Specification of BeagleBoard xM

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
DM3 730	ARM-Cortex A8	Power VR SGX 530	TMS 320 C64 x+	512	4 usb, DVI-D, S-video, 3.5mm Audio	microSD /Fast Ethernet	McBSP, DSS, I^2C, UART, McSPI, PWN, JTAG, Camera Interface	Ubuntu, XBMC, Android, Angstrom Linux	$149

Applications: Medical Equipment's, IoT Devices, Robotics, RC Helicopters.

3. Beaglebone [13]: Beaglebone was launched on October 31, 2011. This board is powered by AM335x 720MHz ARM Processor. This board is regarded as first fully

functional Linux Credit-card sized computer and also facilitates the users to run Android 4.0 (Icrecream Sandwich) along with Ubuntu operating system.

Figure 5. Beaglebone

Table 3. Technical Specification of Beaglebone

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
AM3358/9	ARM-Cortex A8	Power VR SGX530	N/A	256	1 USB, Cape Add-ons	Fast Ethernet	UART, PWM, GPMC, MMC, SPI, I2C, ADC, CAN bus, Timers, JTAG	Ubuntu, Android 4.0, Angstrom Linux	$89

Applications: IoT, Cloud Computing, Super Computer (Cluster of Board's), 2.4 GHz RC Planes.

4. Beaglebone Black [14]: Beaglebone Black is currently most widely sold board worldwide because of its low-cost. Beaglebone black is regarded as most utilized Beaglebone board amongst all boards available till date for various applications and hardware based projects and has support of developers and hobbyists communities worldwide. It is powered by AM335x 1GHz ARM Cortex A8 processor and supports 3D graphics acceleration. Because of its configuration this board can boot Linux in less than 10 seconds.

Figure 6. Beaglebone Black

Table 4. Technical Specification of Beaglebone Black

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
AM 335 8/9	ARM - Cortex A8	Power VR SGX 530	N/A	512	1 USB, Micro-HDMI, cape add-ons	Fast Ethernet	UART, PWM, GPMC, MMC, SPI, I2C, ADC, CANbus, Timers, JTAG	Ubuntu, Android, Debian, Cloud 9 IDE on Node.js w/Bones cript Library	$55

Applications: Robotics, Solar Technology, Full-Fledged Portable PC, Spider Bot, Camera Drones.

5. SeeedStudio Beaglebone Green (BBG) [15-16] : Seeedstudio Beaglebone Green board is based on open-source hardware design of Beaglebone black and developed under joint effort by Beagleboard.org and Seeed Studio. The board is powered by AM335 1GHz ARM Cortex-A8 processor and supports 3D graphics acceleration. This board facilitates 2 Grove connectors and supports wide connection of Grove sensors.

Figure 7. SeeedStudio Beaglebone Green

Table 5. Technical Specification of Beaglebone Green

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
AM335x	ARM-Cortex A8	Power VR SGX530	N/A	512	1 USB, Micro-HDMI	Fast Ethernet	UART, PWM, GPMC, MMC, SPI, I2C, ADC, CAN bus, Timers, JTAG	Ubuntu, Android, Debian, Cloud 9 IDE on Node.js w/Bonescript Library	$39

Applications: Smart Homes, IoT Gadgets, DIY Projects based on Smart Lightning, Robotics, High-End Surveillance Drones.

6. Beagleboard-X15 [17]: Beagleboard-X15 would be launched in November 2015. This board is basically tailored for performance based Linux power users and will facilitate high-speed interfacings and connectivity options. This board would be powered by TI AM5728 1.5 GHz ARM Cortex-A15 with 2GB DDR3 RAM.
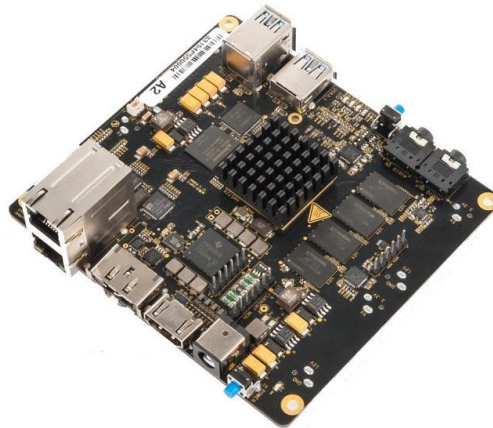

Figure 8. Beagleboard X-15

Table 6. Technical Specification of Beaglebone X-15

SoC	CPU	GPU	DSP	RAM	Connectivity Options(Audio/ Video)	Storage/ Network Option	Internal Modules	Software	Price
Sitara AM5728	ARM-Cortex A15	Dual Power VR SGX 544	Dual TMS 320C 66X	2 GB	3 USB 3.0, 2 USB 2.0, HDMI, LCD via expansion	Gigabit Ethernet	UART, GPMC, SPI, I2C, ADC, CAN bus.	Ubuntu, Android, Debian, Cloud 9 IDE on Node.js	TBA

Applications: Network Security, Portable Linux Power Machine, Drones, Robotics, Telecommunication, Sensor Network, IoT, Super Computing *etc*.

4. Research Areas/Scope for Project Development's

In this section, various research areas would be enlisted in tabular form which will provide wide scope for researchers to research and develop wide range of products on various areas of technology.

Table 7. Research Areas & Project Outcomes/Products of Beaglebone Boards

Research Area	Possible Research Outcomes/Products Development/ Research and Development Projects
Robotics	2 Balances Robots, Master/Slave Robot, Hexapod Robot, Legged Robot, Prowlerbot, Line Follower, RHEX Robot, Robotic ARM, Lego Based Robots, Cape, BeagleBot, OpenROV
Smart Homes	Smart Home Management and Energy Monitoring, Pour Steady, Home Cleaning Intelligent Systems, Debrew, Smart Home Security Management
Drones	Quadcopter, RC Planes, Octocopters, Bi-Copters, Surveillance Drones, Hex-copters
Network Security	Linux Based Encryption, Cryptography, Proxy Server, Linux Secured Server Deployments, Network Traffic Monitoring, Internet Server
Cloud Computing	Cloud Server, Cloud Security, Embedded Cloud Computing, Cloud based Hosting, Web Server, Cloud Computing Cluster Development, Virtualization, Cloud Load Balancing, Cloud Based Fault Tolerant Research.
IoT	IoT Devices, Smart Gizmos, Kitchen Automation, Sensor Based communication technology, NFC, Smart Money Transfer Technology, IoT Development Kits
Sensors Integration	All types of Analog and Digital Sensors for wide applications in Homes, Military, Irrigation, Automation, Medical, Automobiles, Nuclear Power Plants, Smart Grids, and Intelligent Production Machines.
Solar Technology	Smart Solar Tracking System, Solar Generators *etc*.
Open Source Platforms/Applications	Linux Development, Programming (All Languages), openCV

5. Conclusion & Future Scope

5.1 Conclusion

In this paper, a comprehensive review of Beaglebone board's technology is being carried out with varied applications and technical specifications. Beaglebone being ARM based board provides efficient, smart, reliable and flexible platform to various professionals, researchers and embedded systems enthusiasts to take up this board for developing various live and ready to use market implementation projects. Beaglebone community is contributing a lot in research and is growing day by day. Beaglebone boards with improved configurations and connectivity options are launching at regular intervals in this area providing more project development options, high performance and making portable boards full-fledged Linux and cloud computing servers.

In this paper, various research areas which can be taken up by researchers is also being mentioned for providing them with varied options of research applications.

5.2 Future Scope

In future, we would be working on Beaglebone Black for developing efficient and self-controlled Surveillance Drone and Out-of-the-Box Energy Efficient Wireless Sensor Network IoT based Kit.

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